DSN Telemetry System Performance Using a Maximum Likelihood Convolutional Decoder

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This report describes results of telemetry system performance testing conducted at Goddard Merritt Island Space Flight Station using DSN equipment and a Maximum Likelihood Convolutional Decoder (MCD) for code rates 1/2 and 1/3, constraint length 7 and special test software. The test results confirm the superiority of the rate 1/3 over that of the rate 1/2. The overall system performance losses determined at the output of the Symbol Synchronizer Assembly are less than 0.5 dB for both code rates. Comparison of the performance is also made with existing mathematical models. Error statistics of the decoded data are examined. The MCD operational threshold is found to be about 1.96 dB.

I. Introduction

In the past, numerous papers have been written on the subject of DSN telemetry system performance using a code rate 1/2, constraint length 7[1], Maximum Likelihood Convolutional Decoder (MCD) (Refs. 1-3). However, recent attention has been focused on the use of the built-in rate 7:1/3 decoding capability of the MCD for improved telemetry system performance. This may provide an alternate approach to other enhancements being considered; for example, it may allow the use of S-band rather than X-band for some phases of a mission.

In order to verify and analyze the rate 7:1/3 performance of the MCD, tests were conducted at the Merritt Island Goddard Space Flight Center Station using DSN equipment for both code rates. Results and analyses of these tests are provided herein.

[1]For convenience, we shall write this as "a code rate 7:1/2" or simply "a rate 7:1/2."

II. Test Objectives and Implementation

The objectives of the tests were:

(1) To obtain the decoding performance of the MCD, i.e., to obtain plots of bit error probability or bit error rate (BER) vs ST_B/N_0 at the input of the decoder. The BER's of interest are between 10^{-6} and 10^{-2} and the expected ST_B/N_0 is from +1.0 to +5.0 dB.

(2) To obtain the system decoding performance, i.e., to obtain plots of BER vs ST_B/N_0 at the input of the receiver.

(3) To discover the minimum operational point of the telemetry system.

(4) To discover the mechanisms that limit the operating system to this minimum operational point.

(5) To obtain node synchronization change frequencies, i.e., the number of node synchronization changes per the number of decoded bits.

The data rates selected for these tests were 3.6, 5.6, 6.4, and 7.2 kbps. The test conditions are given in Table 1.

To achieve the above objectives, typical DSN telemetry system test equipment consisting of the Simulation Conversion Assembly (SCA), microwave equipment (UWV), Receiver Assembly (RCV), Subcarrier Demodulator Assembly (SDA), Symbol Synchronizer Assembly (SSA), and the Telemetry Processor Assembly (TPA)/MCD was used (see Fig. 1). All tests were configured with the S-band Block III receiver using 12–Hz design point loop noise bandwidth range, Block III SDA at medium-loop bandwidth, Block III SSA at narrow/narrow-loop bandwidth, modulation index of 72 deg (carrier suppression of -10.2 dB), and PN code data pattern for both code rates. The ST_B/N_0 values were established at the receiver input using the Y-factor technique (Ref. 4). The system operational software was employed to provide SSA symbol signal-to-noise ratio (SNR). To determine the MCD BER and error statistics, use was made of a program called MCDPEP to record decoded telemetry data and another program called MDAP to analyze the recorded data (Ref. 3). To obtain MCD SER, the BER line (original symbols) from the SCA to the SSA was connected.

The output of MDAP contained normalization rate (NR,a mechanism in the decoder used to indicate the quality of the input data (Refs. 2 and 8)), MCD BER, MCD SNR (a quantity derived from the decoder normalization rate), number of node sync changes, and burst error statistics.

For each bit rate and ST_B/N_0 value, a data run was made for the rate 1/2 and then for the rate 1/3. This was accomplished by merely reconfiguring the SCA and the MCDPEP software. This method was utilized to reduce the possibility of introducing errors in the Y-factor setup. After each pair of data runs, the Y-factor was checked for drift. In addition, the receiver AGC was monitored continuously for drift.

III. Analysis

A short discussion of system loss and the experimental test results are presented in this section.

A. System Loss

Mathematical loss models of the various telemetry subsystems (i.e., radio loss, subcarrier demodulation loss, bit sync and detection loss, and waveform distortion loss) have been extensively proposed in the past (Refs. 5 and 6); they will not be repeated here. A software implementation of selected loss models, called TAP, is described in Ref. 6. For insight and comparison, a typical printout of this loss-model program for radio (receiver) loss, SDA loss, SSA loss, and other important system parameters is tabulated in Table 2 for the same conditions as stated in Table 1 for the experimental tests. Table 3 provides summaries of Table 2. Note that the loss-model program contains no waveform distortion loss calculation capability.

B. Test Results

The test results in terms of BER, number of normalizations per bit, average normalization rate, number of bursts per bit, average number of errors per burst, average burst length, maximum burst length of each run, number of error-free runs (EFR) per bit, total number of error-free runs, SSA output SER, and node synchronization change frequency (Refs.1-3) are tabulated in Table 4. Five runs were made for each of tests A4, B4, C4, and D4. This is to provide confidence in determining node sync change frequencies. The results were consistent; the averages and standard deviations of these tests are given in Table 4. In order to confirm the first run results, a rerun was obtained for tests A5, A6-1/3, and B6-1/3. Averages and standard deviations of these tests are also shown in Table 4. The accuracy of a Y-factor setting for a specific ST_B/N_0 is approximately ±0.5 dB (based on output SNR's calculated by the MCD and SSA). Furthermore, it was discovered that (see Table 5):

(1) The system operational software could only handle ST_B/N_0 levels above 1.96 dB (believed to be due to the MCD operating threshold), below which the SSA initialized with the software would not achieve lock.

(2) The system losses at the Merritt Island station (MIL-71) were about one decibel worse than those at JPL Pasadena Compatibility Test Area (CTA-21).

Therefore, tests with ST_B/N_0 levels of 1.0, 1.7, and 2.0 dB could not be performed.

It should be pointed out that the SSA SNR and MCD SNR printed out at the Terminet are provided by two special programs contained in the TPA operational software program.

The first program is used to correct the bias of the SSA SNR at low SNR (<5 dB). It is based on a curve fit of Fig. 21 in Ref. 7 for an internal SSA SNR of 26 dB (measured at CTA-21), giving the estimated SSA SNR (dB) as[2]:

$$R_e = -10 \log \left(10^{-R_i/10} + 10^{-R_0/10}\right) \qquad (1)$$

[2]Developed by G. L. Dunn and R. Bunce.

where

R_i = internal SSA SNR = 26 dB

$$R_0 = \frac{-(2 - R_a) + \sqrt{(2 - R_i)^2 + 4\,(R_a + 5)}}{2} \qquad (2)$$

and

R_a = actual input SSA SNR (dB)

Using Eqs. (1) and (2) to estimate the SSA SNR output instead of the exact results from Ref. 7 yields an error of less than 0.14 dB over the range of -5 to 50 dB. By solving Eqs. (1) and (2), the actual SNR expressed in terms of the estimated SSA SNR is as follows:

$$R_a\,(\text{dB}) = \frac{(R + 1)^2 - 6}{R + 1} \qquad (3)$$

where

$$R = \begin{cases} -10 \log \left(10^{-R_e/10} - 10^{-R_i/10}\right) \text{for } R_e \leqslant 5 \text{ dB} \\ R_e \text{ otherwise} \end{cases} \qquad (4)$$

where R_e and R_i have been defined previously.

Equation (3), together with Eq. (4), is used to correct the SSA SNR bias.

The second program provides a system output SNR estimate determined from the MCD normalization rate. The program presently employs the algorithm derived from the Linkabit convolutional decoder model LV7015 implemented in Spain as part of the early telemetry system performance analysis (Ref. 2). The algorithm is

$$ST_B/N_0, \text{dB} = \frac{2.9664}{\overline{N}_c + 0.08} + 5.1218 - 0.2252\overline{N}_c$$

where $\overline{N}_c$ is the average normalization counts (= $192\overline{N}_b$, $\overline{N}_b$ = average normalizations per bit). Due to certain design differences (Ref. 1), this algorithm provides only approximate values of ST_B/N_0 at the MCD output (see Fig. 2).

Plots of BER vs receiver ST_B/N_0 (dB) for all tests (Tests 4 through 6 of test series A through E) are shown in Fig. 3. The rate 1/3 performance is about one-half of a decibel better than that of rate 1/2. This is in agreement with previous simulation results (Ref. 8). The acceptance test data at 250 kbps are also shown in the figure. They were for the MCD alone and included no system losses. The experimental test data show about one decibel degradation from the above ideal data. However, direct comparison of the two cannot be made due to the differences in bit rate and other test conditions.

The measured and calculated losses of the telemetry system considered are shown in Fig. 2. One can see that the measured losses are higher than the calculated ones. This is due to the approximate loss models and the neglect of other loss effects such as the waveform distortion loss.

Figures 4 and 5 provide graphical representations of error-free run size R vs probability that R is exceeded and burst length size B vs probability that B is exceeded. For comparison, each graph displays the results of both rates 1/2 and 1/3. The data indicate no clear trend for rate 1/3 to be superior to rate 1/2 with regard to error-free run data. However, in all cases, rate 1/3 is superior to that of rate 1/2 for the burst length data.

Figure 6 makes comparison of the average burst length and average number of burst errors vs MCD input ST_B/N_0 for tests A4-1/2, A4-1/3, and LV7015-1/2. The other remaining tests yield a similar result and thus are not shown.

IV. Summary

Most of the test objectives were achieved. The decoding performance of the MCD is shown in Fig. 3. The telemetry system decoding performance is summarized in Fig. 2. The minimum operational point of the telemetry system is found to be approximately 1.96 dB (MCD ST_B/N_0 for rate 1/2, see Table 5), below which the SSA initialization with the present system operational software could not be achieved (believed to be due to the MCD operating threshold). (The present system operational software does not have the capability to handle the 1/3 rate.) This leads to elimination of certain low ST_B/N_0 tests. Finally, due to the nature of the decoder, the node synchronization change frequencies, i.e., the number of node synchronization changes per the number of decoded bits, of only low ST_B/N_0 were obtained (given in Table 4). For high ST_B/N_0 tests, the time specified in the test conditions was not sufficiently long to generate a node sync change.

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Table 1. Telemetry performance test conditions

RF band: S; mod index: 72°; data pattern: PN code; RCV: BLK III at 12 Hz W_{LO}; SDA: BLK III, medium; SSA: BLK III, narrow/narrow; subcarrier frequency: 1.44 MHz

Bit rate, kbps	Test ID	P_T/N_0, dB	ST_B/N_0, dB	Expected BER	Time, min	Expected bits	Bit errors
7.2	A1	40.03	1.0	1.2×10^{-1}	2	8.64×10^5	10^5
	2	40.73	1.7	1.8×10^{-2}	2	8.64×10^5	1.6×10^4
	3	41.03	2.0	7×10^{-3}	2	8.64×10^5	6049
	4	42.03	3.0	3×10^{-4}	2	8.64×10^5	259
	5	43.03	4.0	1.5×10^{-5}	30	1.3×10^7	194
	6	44.03	5.0	9×10^{-7}	60	2.6×10^7	23
3.6	B1	37.02	1.0	1.2×10^{-1}	4	8.64×10^5	10^5
	2	37.72	1.7	1.8×10^{-2}	4	8.64×10^5	1.6×10^4
	3	38.02	2.0	7×10^{-3}	4	8.64×10^5	6048
	4	39.01	3.0	3×10^{-4}	4	8.64×10^5	259
	5	40.02	4.0	1.5×10^{-5}	60	1.3×10^7	194
	6	41.02	5.0	9×10^{-7}	120	2.6×10^7	23
5.6	C1	38.94	1.0	1.2×10^{-1}	2.6	8.64×10^5	10^5
	2	39.64	1.7	1.8×10^{-2}	2.6	8.64×10^5	1.6×10^4
	3	39.94	2.0	7×10^{-3}	2.6	8.64×10^5	6048
	4	40.94	3.0	3×10^{-4}	2.6	8.64×10^5	259
	5	41.94	4.0	1.5×10^{-5}	38.6	1.3×10^7	194
	6	42.94	5.0	9×10^{-7}	77.3	2.6×10^7	23
6.4	D1	39.52	1.0	1.2×10^{-1}	2.3	8.64×10^5	10^5
	2	40.22	1.7	1.8×10^{-2}	2.3	8.64×10^5	1.6×10^4
	3	40.52	2.0	7×10^{-3}	2.3	8.64×10^5	6048
	4	41.52	3.0	3×10^{-4}	3.3	8.64×10^5	259
	5	42.52	4.0	1.5×10^{-5}	33.8	1.3×10^7	194
	6	43.52	5.0	9×10^{-7}	67.5	2.6×10^7	23

Table 2. Typical telemetry system parameters and losses obtained from TAP[a] for both rates 7 = ½ and ⅓

Bit rate, kbps	Test ID	ST_S/N_0, dB	Code rate	SSA ST_B/N_0 estimate dB	SDA loop noise BW, Hz	Carrier loop noise BW, Hz	Carrier power, dBm	RCV loss, dB	SDA loss, dB	SSA loss, dB	System loss, dB	SER %
7.2	A4	3.0	1/2	1.33	0.38	99.17	−150.7	0.162	0.049	0.024	0.235	8.43
			1/3	0.64	0.33	99.12	−150.7	0.161	0.053	0.033	0.246	13.11
	A5	4.0	1/2	1.88	0.42	104.50	−149.7	0.134	0.042	0.020	0.196	6.04
			1/3	1.01	0.37	104.40	−149.7	0.133	0.045	0.027	0.205	10.31
3.6	B4	3.0	1/2	1.27	0.35	80.94	−153.7	0.285	0.067	0.024	0.376	8.78
			1/3	0.60	0.30	80.88	−153.7	0.280	0.072	0.034	0.386	13.49
		4.0	1/2	1.81	0.39	87.20	−152.7	0.241	0.058	0.020	0.319	6.31
			1/3	0.96	0.35	87.14	−152.7	0.236	0.062	0.028	0.326	10.63

[a]From Ref. 6 under the following conditions:

System noise temperature = 41 K.
Block III bandwidths = RCV - narrow, SDA - narrow, SSA - medium/narrow.
One-way S/X DOP offset (Hz), rate (Hz/sec), time (min) = 0.0, 0.0, 0.0.

Table 3. Percent of loss for the various telemetry subsystems, calculated, wave form loss not included

Code rate	Relative loss, %											
	7.2 kbps			3.6 kbps			5.6 kbps			6.4 kbps		
	RCV	SDA	SSA	RCV	SDA	SSA	RCV	SDA	SSA	RCV	SDA	SSA
1/2	68	22	10	76	18	6	71	20	9	70	21	9
1/3	64	23	13	73	19	8	68	21	11	66	22	12

Table 4. Telemetry system test performance results

Bit rate	Test ID	ST_B/N_0, dB	Code rate	Number of bits, × 10^6	Bit error rate	Number of norms/bit, × 10^{-6}	Avg norm rate	Bursts/bit	Avg errors/burst	Avg burst length	Max burst length	EFRS/bit, × 10^{-5}	Number distinct EFRS	Symbol error rate %	Sync changes/ bit, × 10^{-6}
7.2	A4	3.0	1/2	0.79 ±0.06	(4.47 ±0.72) × 10^{-3}	11.35 ±0.10	11.86 ±2.43	(6.47 ±0.76) × 10^{-4}	7.56 ±0.23	12.86 ±0.39	69 ±7	490 ±48	477 ±53	13.65 ±7.35	8.3 ±4.3
			1/3	0.81 ±0.07	(3.41 ±0.19) × 10^{-3}	11.32 ±0.12	11.22 ±2.10	(5.82 ±0.46) × 10^{-4}	6.15 ±0.15	9.68 ± 0.34	49 ±11	371 ±27	449 ±34	0.98 ±0.20	12.8 ±6.9
	A5	4.0	1/2	12.92 ±0.07	(2.3 ±0.3) × 10^{-4}	10.18 ±0.02	9.88 ±0.63	(4.45 ±0.42) × 10^{-5}	5.11 ±0.14	8.3 ±0.2	44 ±2	22.95 ±2.85	578 ±52	–	0
			1/3	12.88 ±0.11	(1.62 ±0.26) × 10^{-4}	10.14 ±0.06	11.88 ±0.38	(3.85 ±0.55) × 10^{-5}	4.23	6.13 ±0.13	33 ±4	16.15 ±2.55	503 ±70	0.89	0
	A6	5.0	1/2	25.92	9.57 × 10^{-6}	10.26	5.75	2.20 × 10^{-6}	4.35	7.28	21	0.96	62	3.68	0
			1/3	25.92 ±0.05	(0.70 ±0.43) × 10^{-5}	10.15 ±0.02	8.13 ±0.13	(1.99 ±1.14) × 10^{-6}	3.25 ±0.25	5.0 ±0.25	14 ±3	0.71 ±0.43	57 ±30	–	0
3.6	B4	3.0	1/2	0.89	(3.30 ±0.14) × 10^{-3}	11.20	14.01 ±0.28	(4.67 ±0.14) × 10^{-4}	7.16 ±0.36	12.14 ±0.72	62 ±7	335 ±15	405 ±13	2.61 ±1.6	0.90 ±0.4
			1/3	0.89	(1.73 ±0.13) × 10^{-3}	11.20	14.76 ±0.20	(3.20 ±0.16) × 10^{-4}	5.52 ±0.19	8.54 ±0.37	41 ±5	177 ±14	285 ±14	62.47	2.00 ±1.3
	B5	4.0	1/2	13.00	2.54 × 10^{-4}	10.16	9.75	4.92 × 10^{-5}	5.21	8.53	34	25.62	643	0.05	0
			1/3	13.01 ±0.04	(3.34 ±0.05) × 10^{-4}	10.19	12.75 ±0.25	(7.26 ±0.03) × 10^{-5}	4.61	6.94	42 ±2	33.1 ±0.5	930 ±10	0.9	0
	B6	5.0	1/2	25.92	2.5 × 10^{-5}	10.15	6.25	5.33 × 10^{-6}	4.68	7.73	31	2.5	145	–	0
			1/3	25.69	1.14 × 10^{-5}	10.24	8.25	3.0 × 10^{-6}	3.81	5.81	34	1.15	84	–	0
5.6	C4	3.0	1/2	6.21 ±6.65	(3.28 ±0.51) × 10^{-3}	10.87 ±0.63	9.56 ±3.10	(2.70 ±1.9) × 10^{-4}	7.02 ±1.05	11.81 ±1.89	62 ±10	202 ±152	420 ±309	10.18 ±9.79	9.3 ±10.2
			1/3	0.66 ±0.46	(1.88 ±0.17) × 10^{-3}	11.08 ±0.07	11.35 ±0.70	(3.40 ±0.2) × 10^{-4}	5.79 ±0.24	9.02 ±0.44	47 ±12	198 ±18	340 ±36	4.38 ±0.44	3.2 ±1.3
	C5	4.0	1/2	13.18	3.98 × 10^{-4}	10.17	10.63	7.5 × 10^{-5}	5.30	8.72	46	39.83	976	–	0
			1/3	13.13	1.65 × 10^{-4}	10.21	11.75	3.65 × 10^{-5}	4.50	6.62	39	16.52	482	0.86	0
	C6	5.0	1/2	26.14	1.4 × 10^{-5}	10.10	6.38	3.33 × 10^{-6}	4.28	7.15	19	1.46	93	–	0
			1/3	26.61	5.64 × 10^{-6}	10.03	8.25	1.65 × 10^{-6}	3.41	4.82	17	0.57	50	0.33	0
6.4	D4	3.0	1/2	0.42 ±0.21	(1.92 ±0.11) × 10^{-3}	11.20	1.98 ±0.33	(3.8 ±2.7) × 10^{-4}	7.64 ±0.27	12.85 ±0.53	61 ±14	282 ±186	125 ±48	4.55 ±0.11	105.7 ±51
			1/3	0.99	(3.64 ±0.2) × 10^{-3}	11.20	12.54 ±1.05	(5.80 ±0.3) × 10^{-4}	6.58 ±0.07	10.47 ±0.08	62 ±7	381 ±23	535 ±25	10.76 ±2.99	1.8 ±0.4
	D5	4.0	1/2	13.15	5.7 × 10^{-4}	10.19	10.86	9.57 × 10^{-5}	5.94	9.95	55	56.88	1225	0.53	0
			1/3	13.57	1.77 × 10^{-4}	9.73	10.75	4.01 × 10^{-5}	4.42	6.63	55	1.77	548	6.55	0
	D6*	5.0	1/2	26.41	5.45 × 10^{-5}	10.11	7.50	1.09 × 10^{-5}	4.98	8.00	38	5.48	296	–	0
			1/3	26.40	1.5 × 10^{-7}	10.04	5.38	7.58 × 10^{-8}	2.00	3.00	5	0.02	4	–	0

*Signal too high.

Table 5. Operational thresholds in dB

Code rate	SSA ST_S/N_0	JPL tech rqmt MCD ST_B/N_0	CTA-21 Operational software MCD ST_B/N_0	CTA-21 MCD PEP MCD ST_B/N_0	MIL-71 Operational software MCD ST_B/N_0	MIL-71 MCD PEP MCD ST_B/N_0	Voyager expectation, dB/BER
7:1/2	-5.00	3.00	1.96	2.00	3.16	3.17[a]	$2.3/5 \times 10^{-3}$
							$3.96/3 \times 10^{-5}$
7:1/3	-5.00	2.70	–	1.50	–	3.20	$1.7/10^{-2}$

[a]A rough estimate.

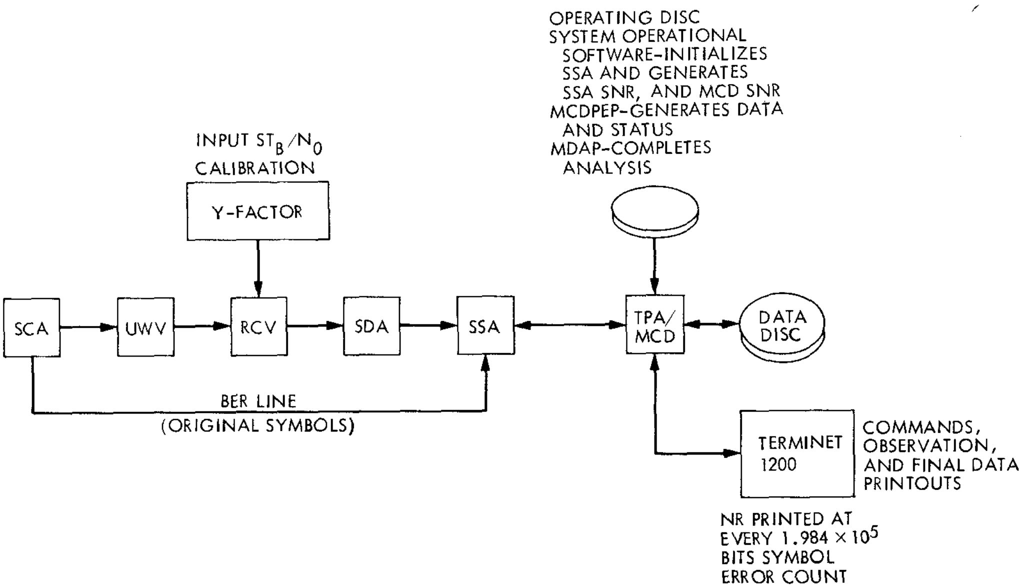
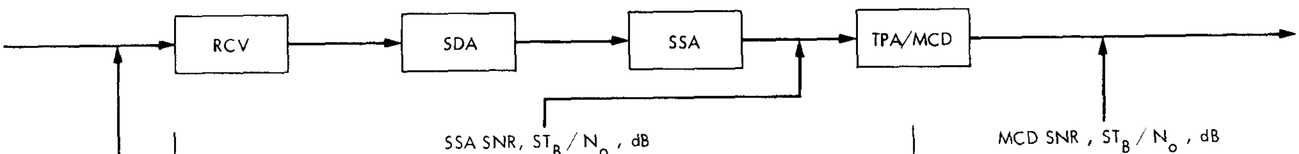


Fig. 1. DSN telemetry system test configuration



CODE RATE	INPUT ST_B/N_0, dB	SSA SNR, ST_B/N_0, dB MEASURED TEST A	B	C	D	CALCULATED (FROM TAB) A	B	C	D	AVG LOSS MEAS	CALC	MCD SNR, ST_B/N_0, dB MEASURED A	B	C	D	AVG LOSS
	3.0	2.53	2.85	2.55	2.28	2.77	2.62	2.72	2.75	.45	.28	1.97	2.08	-	-	.97
1/2	4.0	3.78	3.73	3.42	3.66	3.80	3.68	3.77	3.79	.35	.24	3.32	3.27	2.98	2.93	.88
	5.0	4.90	4.69	4.64	4.41	4.84	4.73	4.80	4.82	.34	.20	4.32	4.14	4.16	3.83	.89
	3.0	2.76	2.69	2.84	2.48	2.75	2.61	2.71	2.73	.31	.30	NOT AVAILABLE				
1/3	4.0	3.48	3.46	3.86	3.71	3.80	3.67	3.76	3.78	.37	.25					
	5.0	4.39	4.68	4.59	5.47	4.83	4.73	4.80	4.82	.22	.21					

NOTES: TEST A 7.2 kbps
TEST B 3.6 kbps
TEST C 5.6 kbps
TEST D 6.4 kbps

Fig. 2. Measured and calculated telemetry performance for code rates 7:½ and ⅓ at various bit rates

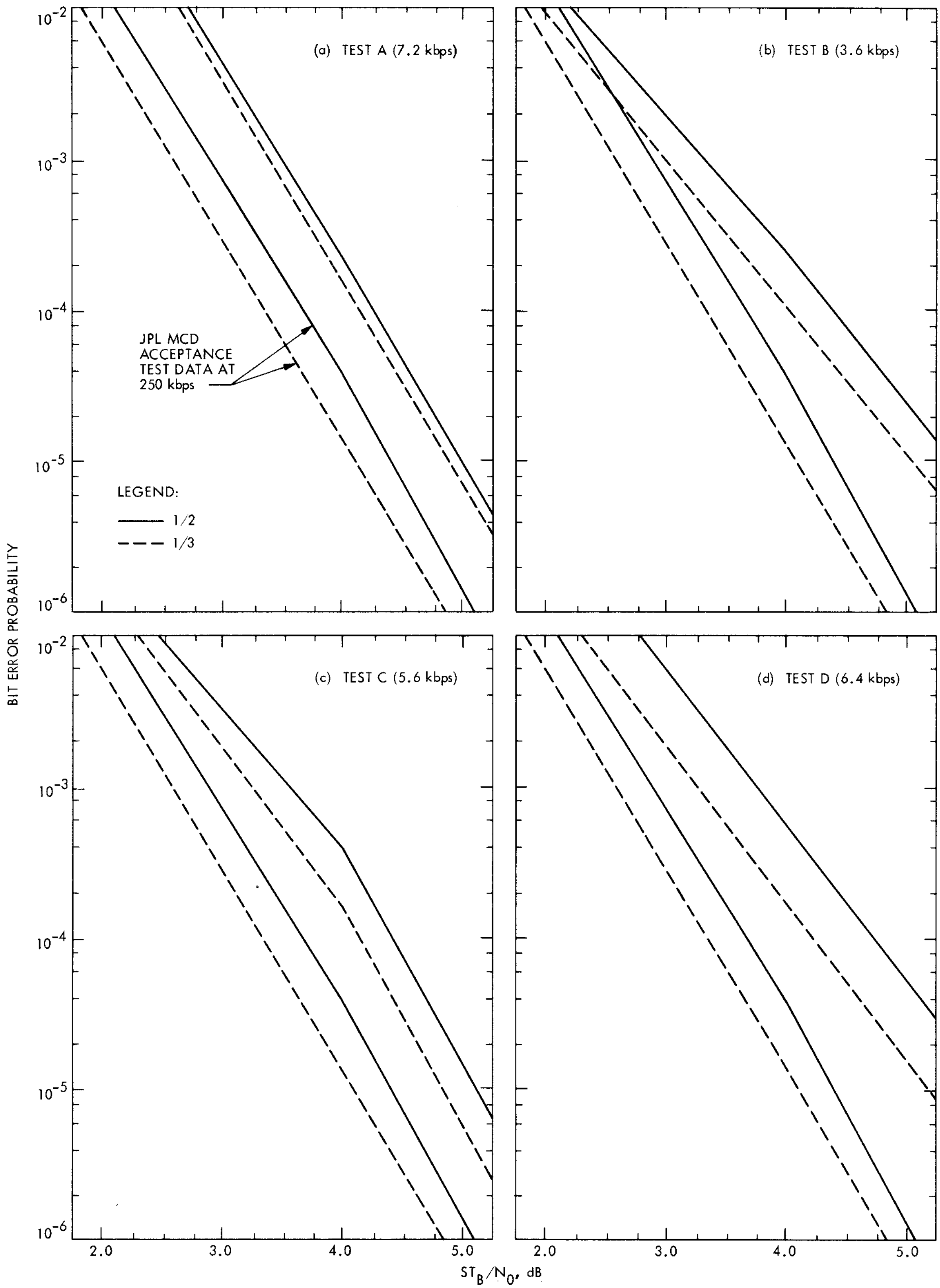


Fig. 3. Bit error probability vs receiver ST_B/N_0 by Y- factor of tests A-D for code rates 7:½ and ⅓

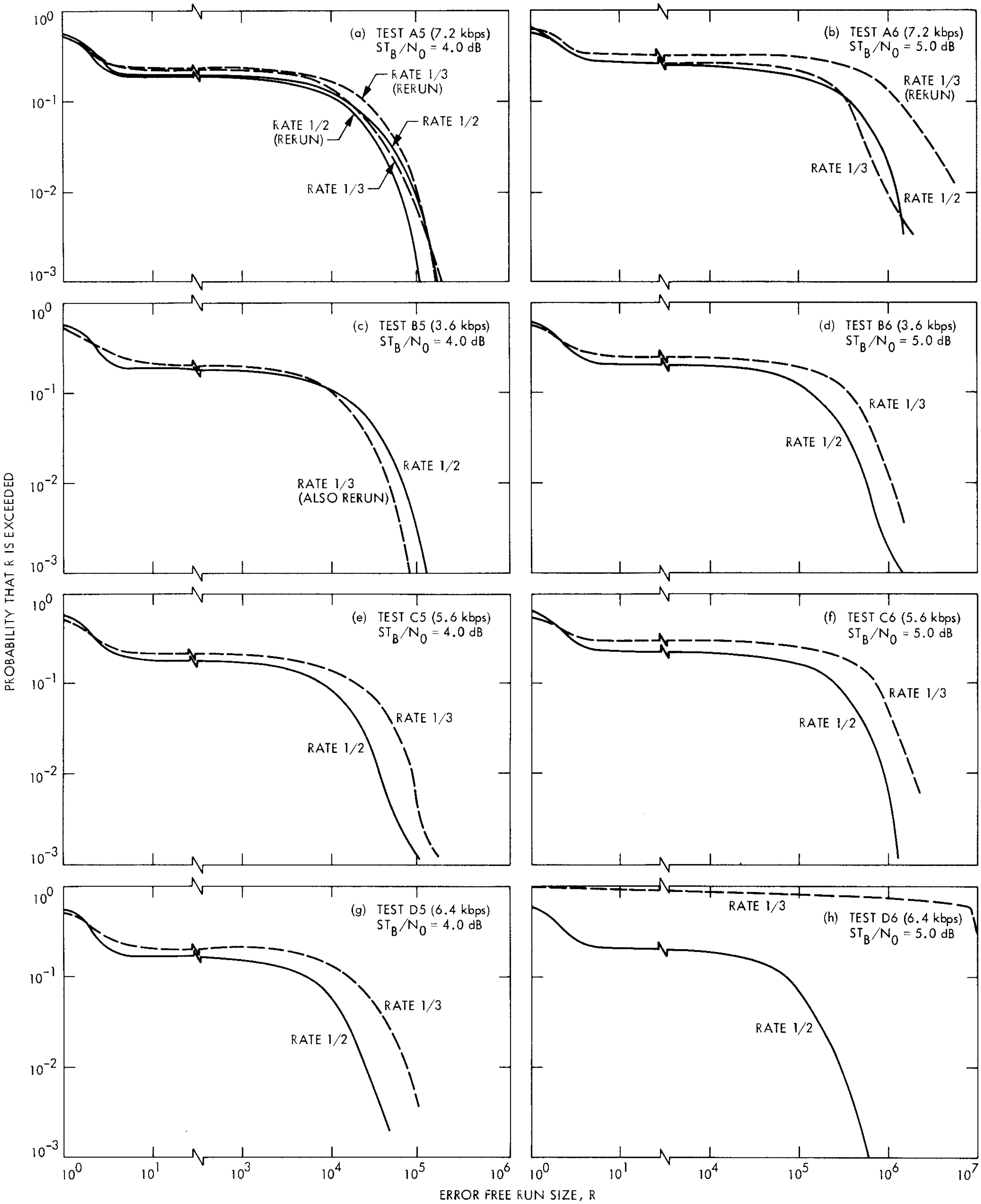


Fig. 4. Error-free run size R vs probability that R is exceeded of tests A5-D6 for code rates 7:½ and ⅓

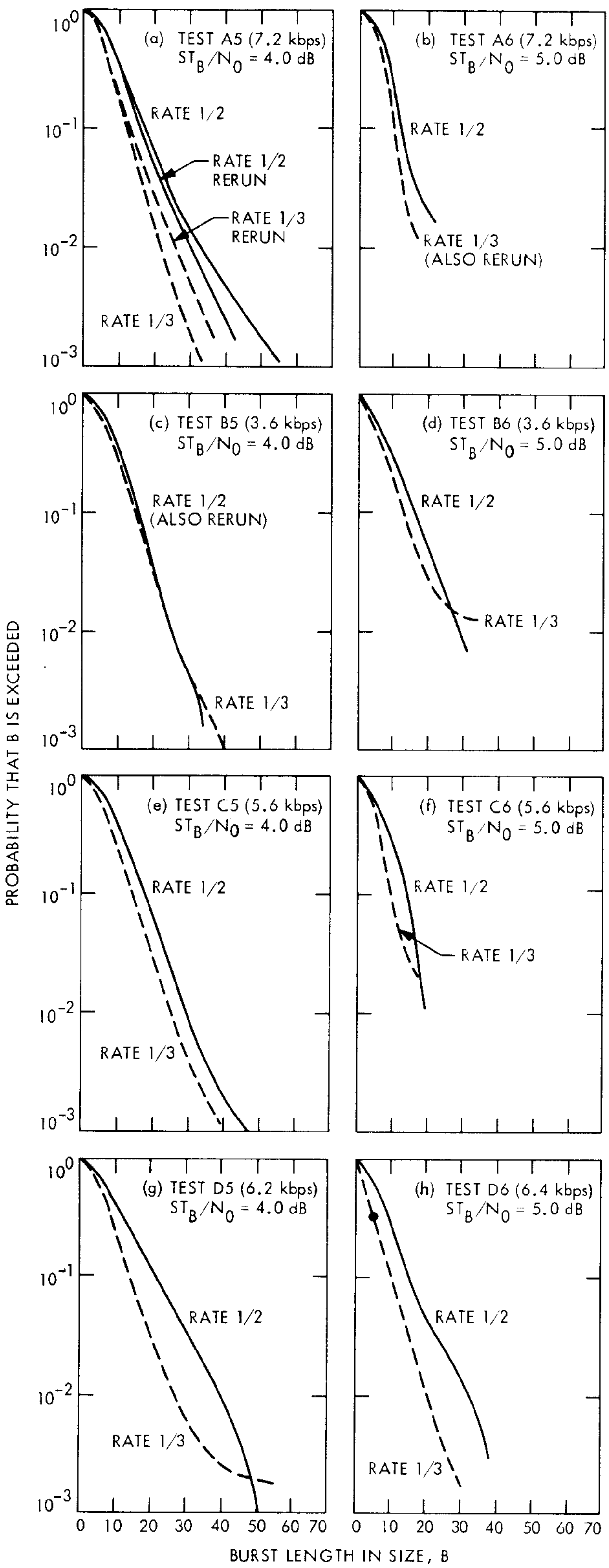


Fig. 5. Burst length size B vs probability that B is exceeded of tests A5-D6 for code rates 7:½ and ⅓

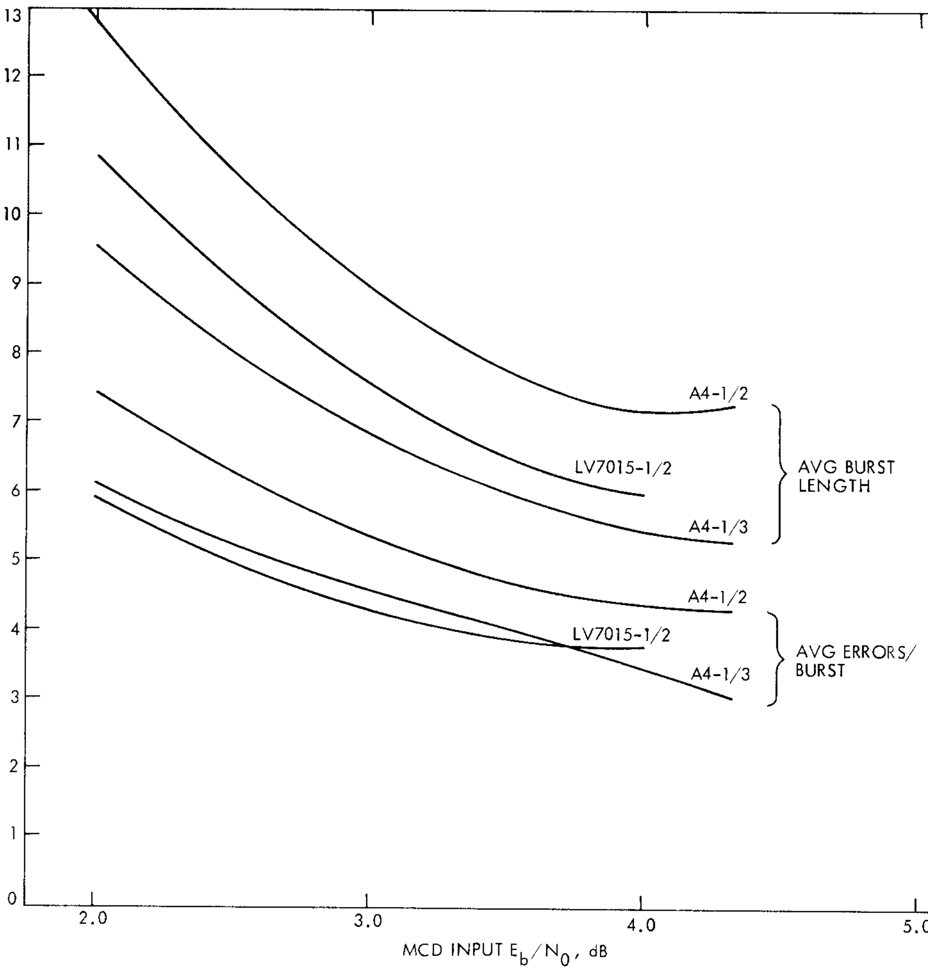


Fig. 6. Comparison of average burst length and average number of burst errors vs MCD input E_b/N_0 for tests A4-½, A4-⅓, and LV7015-½